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TECHNICAL NOTE

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GROUND MEASUREMENTS OF THE SHOCK-WAVE NOISE FROM SUPERSONIC BOMBER AIRPLANES IN THE ALTITUDE RANGE FROM 30,000 TO 50,000 FEET

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SUMMARY

Shock-wave ground-pressure measurements have been made for supersonic bomber airplanes in the Mach number range from 1.24 to 1.52, for altitudes from about 30,000 to 50,000 feet, and for a gross-weight range from about 83,000 to 120,000 pounds. The measured overpressures were generally higher than would be predicted by the theory which accounts only for volume effects. There is thus a suggestion that lift effects on sonic-boom intensity may be significant for this type of airplane for the altitude range of the present tests.

INTRODUCTION

Sonic booms associated with the operation of large supersonic aircraft at moderate altitudes constitute a serious problem. Adverse public reaction and some nuisance damage have already occurred during routine training operations of supersonic bomber aircraft. In the operation of future supersonic transports the sonic-boom problem may be especially critical during the acceleration phase of the flight and, in fact, may determine the minimum acceptable altitude for supersonic flight.

Theoretical methods have been developed (refs. 1 to 4) for calculating sonic-boom pressures. These methods need to be confirmed over a practical range of operating conditions, however, before they can be applied with confidence in making sonic-boom pressure estimates for future aircraft such as the supersonic transport.

Numerous measurements of ground pressures have been made for fighter airplanes for Mach numbers up to 2 and at altitudes to 60,000 feet (refs. 5 to 8). These measured data have been in good agreement with calculations by the method of Whitham (ref. 1), which accounts only for volume effects. Calculations by the method of Walkden (ref. 3) have

indicated that, although lift effects may be negligible for the cases of references 5 to 8, they may become dominant at high altitudes for large airplanes such as the supersonic transport. There is very little experimental information available which can be used to evaluate the influence of lift. The present tests made use of the largest available supersonic airplane, and particular attention was focused on obtaining basic information relative to the role of lift in sonic-boom generation.

Contained herein are ground measurements of shock-wave noise for Mach number and altitude ranges of direct interest for military training operations and for the phase of flight in which future supersonic transports will accelerate to supersonic speeds. The main variables involved in these flight tests are airplane weight and airplane altitude.

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SYMBOLS

d	equivalent body diameter, ft
K_1	ground-reflection factor
K_2	airplane volume-shape factor
K_3	airplane lift-shape factor
l	airplane length, ft
l_w	airplane wing root-chord length, ft
M	airplane Mach number
p_a	ambient pressure at altitude, lb/sq ft
p_o	ambient pressure at ground level, lb/sq ft
Δp_o	measured pressure rise across shock wave at ground level, lb/sq ft
Δp_v	calculated pressure rise across shock wave at ground level based on airplane volume, lb/sq ft
Δp_L	calculated pressure rise across shock wave at ground level based on airplane lift, lb/sq ft

Δp_{V+L}	calculated pressure rise across shock wave at ground level based on airplane volume and lift, lb/sq ft
A	airplane cross-sectional area, sq ft
Δt	time interval between arrival of bow wave and tail wave at ground level, sec
V	airplane ground velocity, ft/sec
W	airplane gross weight, lb
X	distance between shock waves in horizontal plane, ft
x	cylindrical coordinate measured along body axis, ft
y	distance from measuring station perpendicular to flight path, ft

APPARATUS AND METHODS

Test Conditions

Time histories of the noise pressures at ground level were taken during constant-speed and constant-altitude flights of bomber airplanes in the vicinity of Indian Springs Air Force Base, Nevada, during the period from July 29 to August 19, 1960. Data were obtained for an altitude range from 29,800 to 50,000 feet, for a Mach number range from 1.24 to 1.52, and for a gross-weight variation of 83,000 to 120,000 pounds. The bulk of the pressure measurements was made along the flight track of the aircraft, although some data were recorded at lateral distances up to approximately 19 miles from the flight track.

A contour map of the test area is shown in figure 1. Superposed on this map is the planned flight track of the airplanes along with the location of the microphone station, the four microbarograph stations, and the meteorological station. The region in the vicinity of the microphone station was a dry lake bed (as indicated by the hatched area) at an elevation of approximately 3,000 feet and was essentially flat for a radius of about 5 miles in all directions. As can be seen from the contour map, however, mountain ranges existed on either side of the valley in which the measurements were made. Both these mountain ranges contained some peaks with elevations of about 10,000 feet and were located in such a way that the test airplane passed over them during the test run on a heading of about 240° magnetic or its reciprocal. Although

not indicated in figure 1, supersonic turns were accomplished over relatively uninhabited areas at either end of the test run.

Test Airplanes

Photographs of airplanes of the type used in these tests are shown in figure 2. The airplanes had an overall length of 96.8 feet and a gross weight varying from about 83,000 to 120,000 pounds. They were equipped with an external pod, as indicated in the figure, for all flight tests. The cross-sectional area distribution for the airplane equipped with pod is given in figure 3. The test airplanes were operated by U.S. Air Force personnel. Air Force tanker airplanes were used to refuel the test airplanes for the purpose of varying the gross weight during the tests.

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Aircraft Operations

The airplanes were positioned over the test area mainly by means of on-board navigation equipment. In the case of flights above 35,000 feet, clearly visible contrails enabled the ground station to transmit small corrections to the aircraft heading while the aircraft was still at least 20 miles from the test area. No radar or other ground-based tracking equipment was available during these tests. Visual contact was established at the ground station for all flights for which data were obtained, and these observations were used as a basis for estimating the relative lateral position of the airplane. Airplane Mach number, altitude, and gross weight were determined from on-board observations by the flight crew, and the information was relayed to the ground station by radio.

Atmospheric Soundings

Rawinsonde observations were taken at 2- to 4-hour intervals from a weather station about 45 miles from the test area (see fig. 1) during the flights. Measured values of temperature and pressure from these soundings, along with calculated speed-of-sound values, are shown for the various flights as a function of altitude (above 4,000 feet) in figure 4. The standard ICAO atmosphere values (ref. 9) are also shown for comparison. It is seen that the pressure, temperature, and sound-speed gradients do not differ markedly from the standard values and that the variations during the tests are relatively small. Ground temperatures measured independently in the test area were from 93° F to 104° F for all tests.

In addition to the measured quantities, wind velocity and direction were calculated from the rawinsonde data and resolved into components parallel to and perpendicular to the planned airplane flight path. The resulting wind-velocity profiles for the various flights are shown in figure 5 as a function of altitude. Surface wind measurements made at the test site with portable equipment indicated generally northerly winds of 0 to 15 ft/sec with gusts estimated to 30 ft/sec. An exception was noted for flight 3, at which time there were southeasterly winds with gusts estimated at 30 to 60 ft/sec.

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Noise-Measuring Instrumentation

Noise-pressure measurements were obtained with the aid of commercially available condenser-type microphone systems having a useful frequency range from about 5 to 10,000 cps and a flat frequency response (within ±2 decibels) in the range from 10 to 7,000 cps. These systems were calibrated with a 400 cps sine wave at a pressure level of 121 decibels. The signals from all microphones were recorded on an FM tape recorder having a flat frequency response from 0 to 10,000 cps. Tape playbacks of the pressure time histories were made on an oscillograph record having galvanometer elements which were flat from 0 to 5,000 cps. Microphones were shock mounted in 3/4-inch plywood boards which, in turn, were securely anchored by corner stakes to the ground for the ground measurements.

Eight ground-pressure-measuring microphones were located in the test area (see fig. 1) and one microphone was located at the top of a 20-foot mast for the purpose of measuring the free-air pressures. In addition, microbarographs measuring in the range from 0 to 30 cps and operated by the Sandia Corporation were located along a line nearly perpendicular to the flight track (see fig. 1), at distances up to about 19 miles from the flight track. One microbarograph station was located on the designated airplane track about 5 miles from the microphone measuring station.

RESULTS AND DISCUSSION

Pressure Measurements

A summary of the measured microphone ground-pressure data for all flights is given in table I. Some of these data are presented in figures 6 to 9 to illustrate the nature of the results. The values given in table I and shown in figure 6 are averages of the eight microphone recordings for each flight.

Tracings of microphone ground-pressure time histories for three different altitudes and two Mach numbers are illustrated in figure 6. These pressure time histories have the same gross features as those presented in references 5 and 6, which, incidentally, were obtained with similar pressure-measuring equipment. They differ markedly, however, from those of references 5 and 6 in some details. In particular, the rise times are greater and the peaks are broader. The characteristic frequency response of the measuring equipment used is believed to be such that the peaks would be well defined but the pressure time histories between the peaks would be distorted because of the inability of the microphone to follow a slowly varying pressure (ref. 5). It should be noted in figure 6 that the pressure amplitudes are not comparable because of differences in gain settings. These pressure traces were all recorded with the same channel of measuring and recording equipment, and thus the detailed differences are believed to be due to micrometeorological effects. There is also the possibility that the characteristic far-field "N" wave shape had not been able to develop for the conditions of these tests.

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The quantity Δp_o is indicated in figure 6 as the measured peak value of overpressure at ground level due to the bow wave. The period Δt of the pressure disturbances is defined as the time interval between the passage of the bow and tail waves and is indicated also in the figure. It may be seen from the values of table I that peak overpressures in the range from 0.57 to 2.09 lb/sq ft were measured for the conditions of these tests. Likewise, periods of 0.148 to 0.214 second were measured.

Comparison With Theory

For the purpose of comparing the measured pressure results with theory, use has been made of formulas developed in references 1 and 4, for volume and lift effects, respectively, and in reference 1 for time intervals. These formulas are reproduced here in a form convenient for engineering calculation.

Procedure for calculating volume effects.- The expression used for calculating the overpressure due to volume is as follows:

$$\Delta p_v = K_1 \frac{\sqrt{p_a p_o}}{y^{3/4}}\left(M^2 - 1\right)^{1/8} K_2 \frac{d}{l} l^{3/4} \qquad (1)$$

For the present investigation, $K_1 = 1.8$, $K_2 = 0.62$, $l = 96.8$ feet, and $d/l = 0.12$.

Procedure for calculating lift effects. - The equation for overpressures due to lift is as follows:

$$\Delta p_L = K_1 \frac{\sqrt{p_a p_o}}{y^{3/4} {p_a}^{1/2}} \frac{\left(M^2 - 1\right)^{3/8}}{M} K_3 \frac{W^{1/2} {l_w}^{3/4}}{l_w} \tag{2}$$

where, for the calculations presented in this paper, $K_3 = 0.60$, $l_w = 51.9$ feet, and W varies from 83,000 to 120,000 pounds.

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Procedure for calculating time intervals. - In addition to the values of overpressure, time intervals Δt were determined for the conditions of these tests by means of the following expression from reference 5, which is based on volume considerations alone:

$$\frac{X}{l} = \frac{2.22M^2}{\left(M^2 - 1\right)^{3/8}} \frac{d}{l}\left(\frac{y}{l}\right)^{1/4}$$

where X is the distance between the bow and tail shock waves in a plane parallel to the flight path. With a knowledge of X, the time intervals may be calculated from the equation

$$\Delta t = \frac{X}{V} \tag{3}$$

where V is the ground velocity of the airplane. Values of V, along with measured and calculated values of Δt, are given in table I.

Effects of altitude. - A summary of the results of measurements from overhead flights is given in figure 7, in which ground pressures are plotted as a function of altitude. Some information included in this figure is taken from the unpublished work of Gareth H. Jordan and Norman J. McLeod of the NASA Flight Research Center. The curve is calculated from equation (1) (volume component only) for the airplane of the present tests for a Mach number of 1.6. Measurements of the present tests are shown as the solid test-point symbols. Other data for similar bomber aircraft are shown by the open circular symbols. The remaining data points apply to various fighter aircraft. All data points represented by open symbols have been normalized by means of equation (1) to the conditions of the calculated curve.

It can be seen that both the calculated and the measured data indicate a decrease of ground pressures with increasing altitude. The fighter-aircraft data points scatter about the calculated curve but in

general seem to fall somewhat below the calculated values. The bomber data points also scatter about the calculated curve but in general seem to fall somewhat higher than the calculated values.

In order to examine more closely the bomber-aircraft data of the present tests, for which gross-weight information is available, these data have been replotted as a function of altitude in figure 8. The calculated volume component (eq. (1)) is again shown along with the lift component for an assumed gross weight of 120,000 pounds (eq. (2)). Also shown is a hatched area representing the combined lift and volume values computed by the method of reference 4. The open data points represent a gross weight of 83,000 pounds, the solid data points represent a gross weight of 120,000 pounds, and data points with various amounts of shading represent intermediate values of gross weight.

The calculated values of the overpressure component due to volume, represented by the solid curve, are seen to decrease rapidly with an increase in altitude, whereas those due to lift, represented by the dashed curve, decrease at a slower rate. The calculated overpressure component due to lift is seen to be of about the same magnitude as that due to volume at an altitude of about 30,000 feet for this airplane. At higher altitudes the calculated component due to lift is the larger, and at sufficiently high altitudes it would probably dominate. Combined lift- and volume-component values for this particular airplane, as calculated in reference 10 according to the method of reference 4, result in the range of values given by the hatched area for the gross-weight range of the tests. It can be seen that the combined lift-volume calculated values are greater than those based on volume alone at all altitudes and are less than those based on lift alone at the higher altitudes. This result is in qualitative agreement with the prediction made in reference 4 for an airplane configuration approximating that of the test airplane.

It can be seen from figure 8 that the measured data also tend generally to decrease in magnitude with an increase in airplane altitude, although there is considerable scatter. It is significant that the data points generally scatter about the combined lift-volume values of the hatched area. There is thus the suggestion that lift effects are significant for this airplane for the altitude range of the present tests.

<u>Effects of gross weight</u>.- In order to illustrate the effects of gross weight, the data points in figure 8 have been plotted with various amounts of shading to indicate the gross-weight value for each test. With the exception of the three data points at altitudes of 47,000 and 48,500 feet, higher pressure values were measured for the higher gross weights.

In order to determine more clearly the effects of gross weight, the overpressure data of table I have been normalized with the aid of equation (2) and plotted in figure 9 against airplane gross weight. Equation (2) has been solved for the gross-weight factor $W^{1/2}$ and this calculated effect of gross weight on the overpressure due to lift is plotted as the solid curve of figure 9. It may be seen that considerable scatter exists in the experimental data but that the data points scatter generally about the theoretical curve. Because of the limited gross weight range and the inherent scatter in the data, the trend of the data is not readily apparent. If a straight line were fitted to the data by the method of least squares, the resulting slope of this line would be similar to that of the theoretical curve in figure 9 but the associated confidence interval would be poor, so that agreement between theory and experiment could be fortuitous. Although the application of the least squares procedure would admittedly be questionable because of the limited data, the measured effects of gross weight are at least in qualitative agreement with those predicted by equation (2).

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Time intervals.- The time intervals Δt for the conditions of the flight tests have been calculated by means of equation (3) and are listed in table I. Also included in this table are the measured values for comparison. It can be seen that, generally, both the calculated and measured Δt values increase as altitude increases. Likewise, for a given altitude the Δt values tend to increase as Mach number decreases. The measured values scatter about the calculated values for the present tests, whereas for the fighter-type airplane tests of reference 5 the measured values are generally lower than the calculated values.

Other Observations

In addition to measuring the pressures and time intervals near the ground track of the airplane, there was also the opportunity to observe the lateral extent of the ground-pressure pattern, the number of booms, the response of structures, ground motions, and some human reactions.

Lateral spread.- With the aid of the microbarograph equipment noted in figure 1 and the associated operating personnel, observations were made to a distance of about 19 miles from the planned flight track. A summary plot of the observations and measurements at the microbarograph stations is given in figure 10. Pressure amplitude is plotted as a function of lateral distance for flight tests in the altitude range from 30,000 to 50,000 feet at Mach numbers from 1.45 to 1.52. (See table I.) Since the absolute calibration of this microbarograph equipment is not available, only the relative amplitudes of the peak pressures

are given in the figure. Also shown are the calculated cutoff distances due to refraction for the altitude range of the tests, based on the method of reference 2, for which a standard atmosphere is assumed. It can be seen that the relative amplitudes of the pressures fall off generally as lateral distance increases. Some observations and measurements were made at distances in excess of 18 miles, and the resulting experimentally determined cutoff distances were in roughly the same range as those calculated by the method of reference 2.

Number of booms.- Observers near the ground track reported two booms for all flights except number 3, and these observations were supported by the measurements. In the case of flight number 3, three booms were reported, whereas four pressure peaks were recorded by the instruments within a 0.7-second time interval. This unusual occurrence may have been due to either a small change in the flight path of the airplane or to local atmospheric disturbances. It should be noted that unusual surface wind conditions existed at the time of this flight.

L-1457

Structural response.- No structural damage of any kind was observed or reported as a result of these tests. Some large (approximately 6 by 8 feet) plate-glass thermal-pane windows in the test area experienced observable deflections. Windows of two other types used in residential construction which were approximately 3 feet square (one type having nine 1-foot-square panes) were observed to have negligible response even after being scribed.

Ground motion.- There was opportunity during the test to study possible ground motions by means of seismic pickups buried 5 feet below the ground surface. Barely perceptible earth-motion disturbances were noted, and these were judged to be of a localized nature. As a matter of interest, these were greater in magnitude than those due to a fighter airplane flying directly over the test area at extremely low altitudes and high subsonic speeds.

Human reaction.- Even though the sonic booms were observed in a small town located within 5 miles of the designated flight track of figure 1, no complaints were received. Likewise, no complaints were registered from areas over which supersonic turns were made although, of course, these areas were mostly uninhabited.

Some of the observers who were also involved in the fighter-aircraft flight tests of references 5 and 6 were of the opinion that for about equal peak overpressures, sonic booms from the bomber aircraft of the present tests seemed less annoying. It is significant that in the fighter-plane tests of reference 5 the sonic-boom pressure traces having a rounded-off appearance, as observed at lateral stations, were judged to be less objectionable than those of about equal intensity having

short rise times and sharp peaks, as observed near the flight track. The pressure time histories for the bomber aircraft of these tests, as illustrated in figure 6, differed from those of references 5 and 6 in that the rise times are greater and the peaks are broader. The differences in reactions of the observers to the sonic booms of the fighter and bomber tests are believed to result from the differences in the wave shapes.

CONCLUDING REMARKS

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Shock-wave ground-pressure measurements have been made for supersonic bomber airplanes in the Mach number range from 1.24 to 1.52, for altitudes from about 30,000 to 50,000 feet, and for a gross-weight range from about 83,000 to 120,000 pounds. The measured overpressures were generally higher than would be predicted by the theory which accounts only for volume effects. There is thus a suggestion that lift effects on sonic-boom intensity may be significant for this type of airplane for the altitude range of the present tests.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Field, Va., March 15, 1961.

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TABLE I.- LOG OF FLIGHTS FOR SONIC-BOOM INVESTIGATION

Flight	Date	Altitude, ft	Mach number	Airplane ground velocity, V, ft/sec	Gross weight, lb	Airplane heading, deg	Estimated lateral distance, miles	Δp_o, lb/sq ft	Measured Δt, sec	Calculated Δt (eq. (3)), sec
1	7/29/60	45,000	1.50	1,434	109,100	240	1 South	1.90	0.168	0.172
2	7/29/60	50,000	1.51	1,420	92,300	230	4 South	.57	.204	.180
3	8/15/60	47,000	1.45	1,400	120,000	240	3 South	.69	.214	.180
4	8/15/60	50,000	1.45	1,391	110,000	239	6 South	1.33	.211	.190
5	8/16/60	40,000	1.52	1,466	90,100	060	4 South	.98	.171	.178
6	8/16/60	48,500	1.50	1,435	83,000	240	3 South	1.33	.182	.180
7	8/16/60	48,000	1.50	1,435	110,000	240	5 South	.86	.199	.182
8	8/16/60	44,400	1.50	1,442	95,100	060	6 South	1.04	.175	.176
9	8/16/60	30,000	1.50	1,532	86,000	255	1 North	2.09	.148	.159
10	8/18/60	46,500	1.50	1,440	100,000	242	3 North	1.13	.193	.176
11	8/18/60	30,000	1.29	1,322	93,000	060	0	.92	.164	.159
12	8/19/60	45,000	1.50	1,447	110,000	243	3 South	1.49	.200	.176
13	8/19/60	45,000	1.52	1,465	115,000	239	2 South	1.66	.197	.172
14	8/19/60	40,000	1.52	1,480	102,000	043	2 South	1.64	.164	.166
15	8/19/60	29,800	1.24	1,269	120,000	247	1 South	1.80	.177	.167
16	8/19/60	40,000	1.50	1,460	105,000	057	1 South	1.50	.162	.165

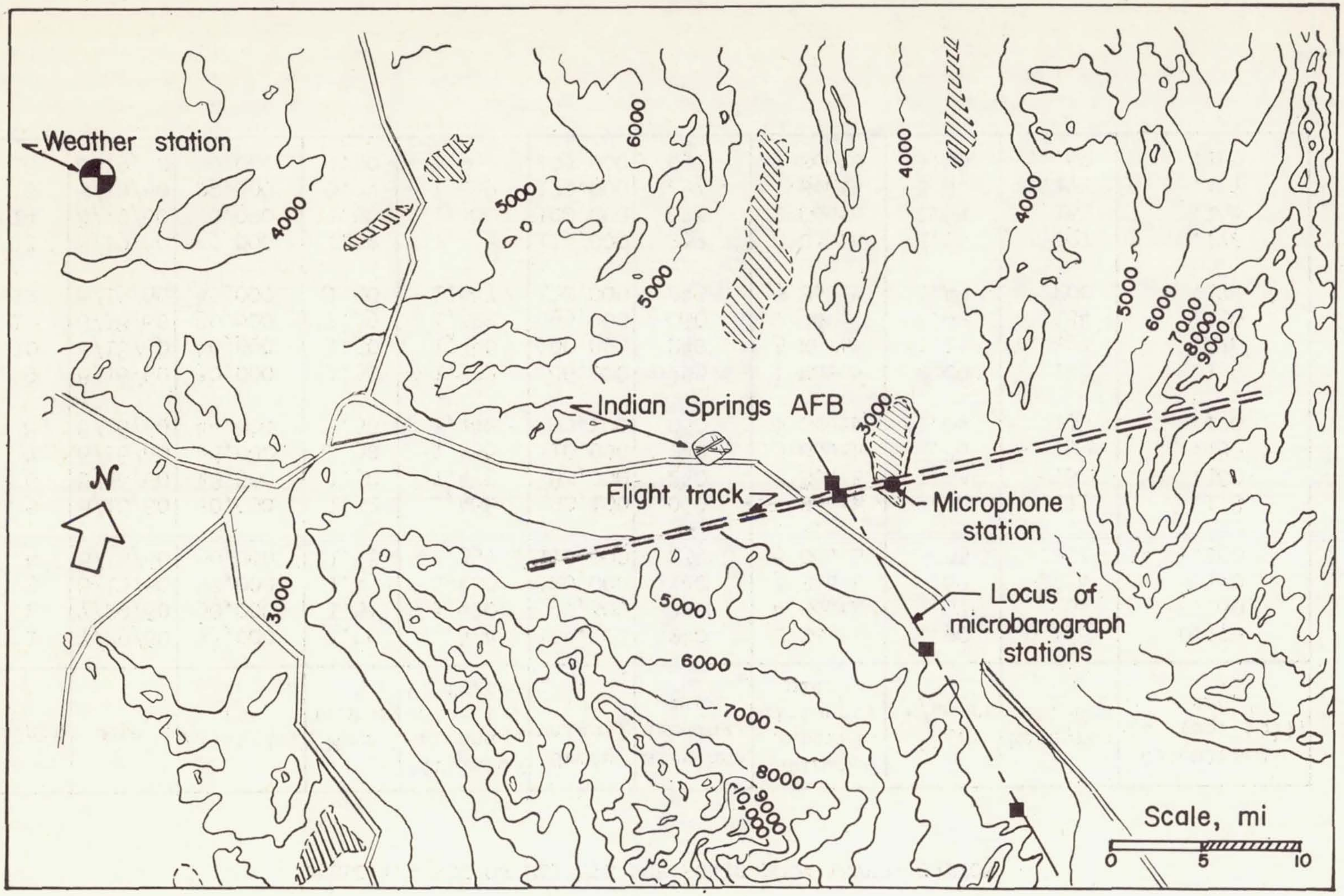
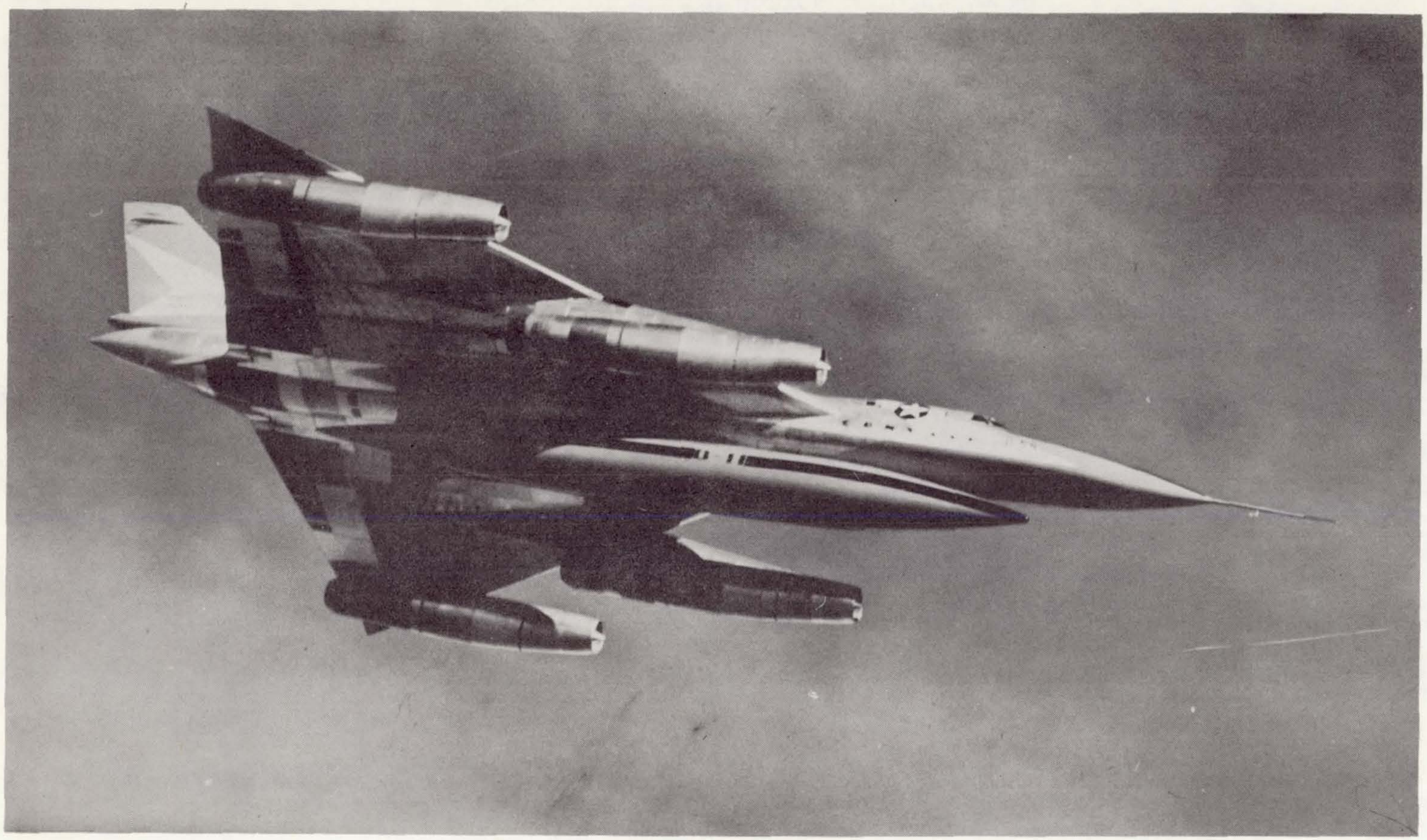


Figure 1.- Contour map of test area showing planned airplane flight track and location of microphone, microbarograph, and meteorological measuring stations. Contour interval of 1,000 feet.

(a) Side view. L-61-1030

Figure 2.- Photographs of aircraft of the type used in the investigation. (Courtesy of Convair Division, General Dynamics Corporation.)



(b) Bottom view. L-61-1031

Figure 2.- Concluded.

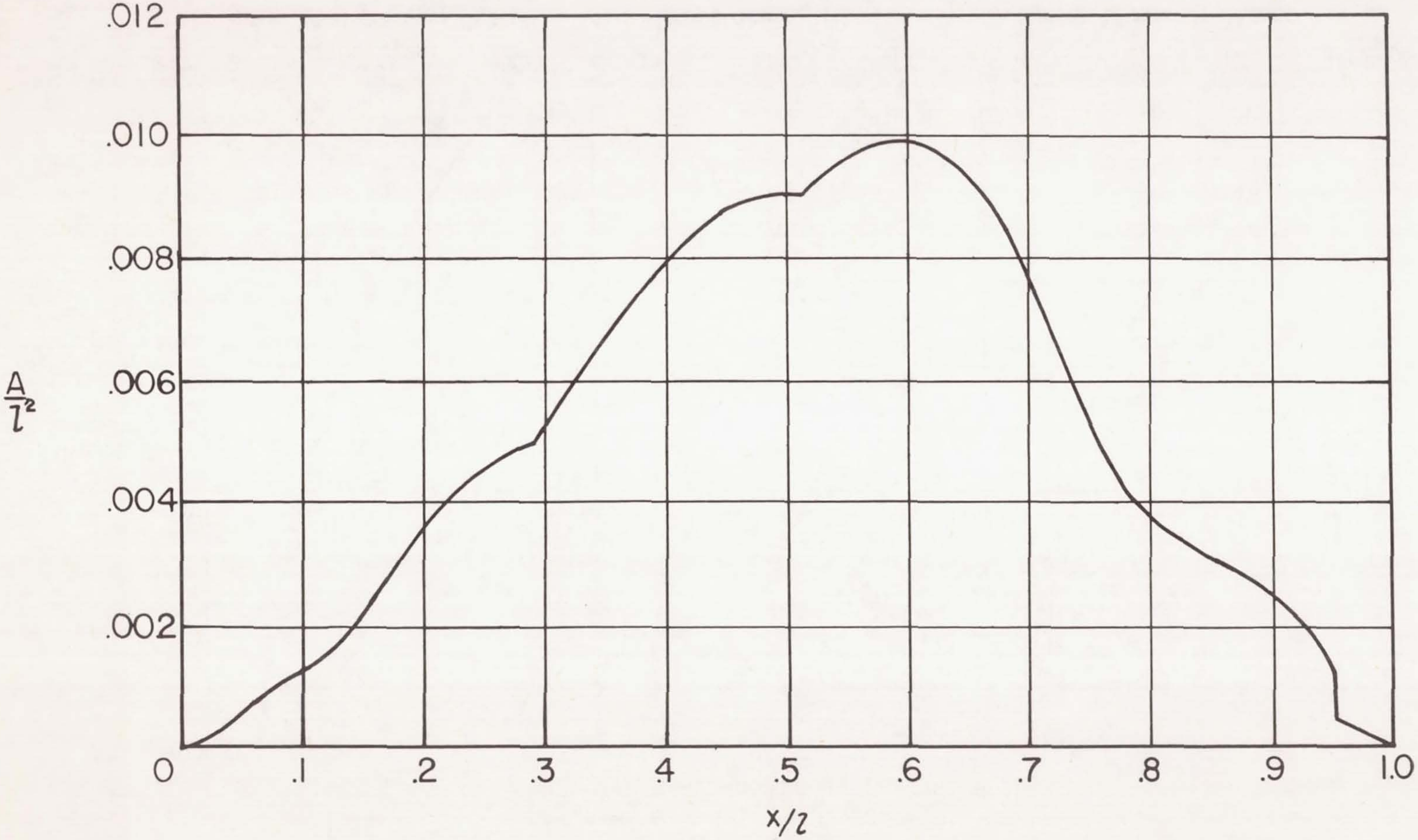


Figure 3.- Cross-sectional area distribution of test aircraft.

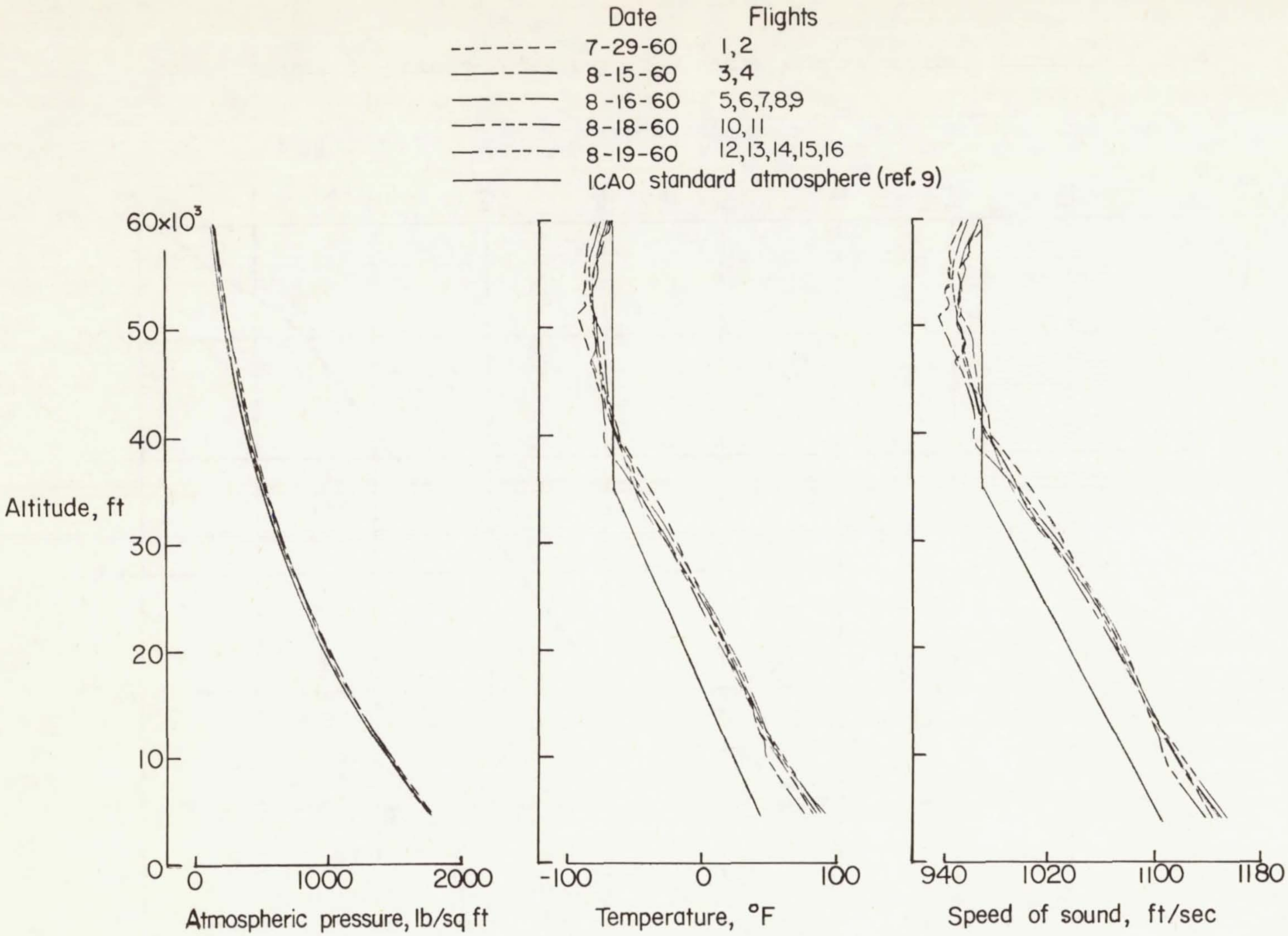
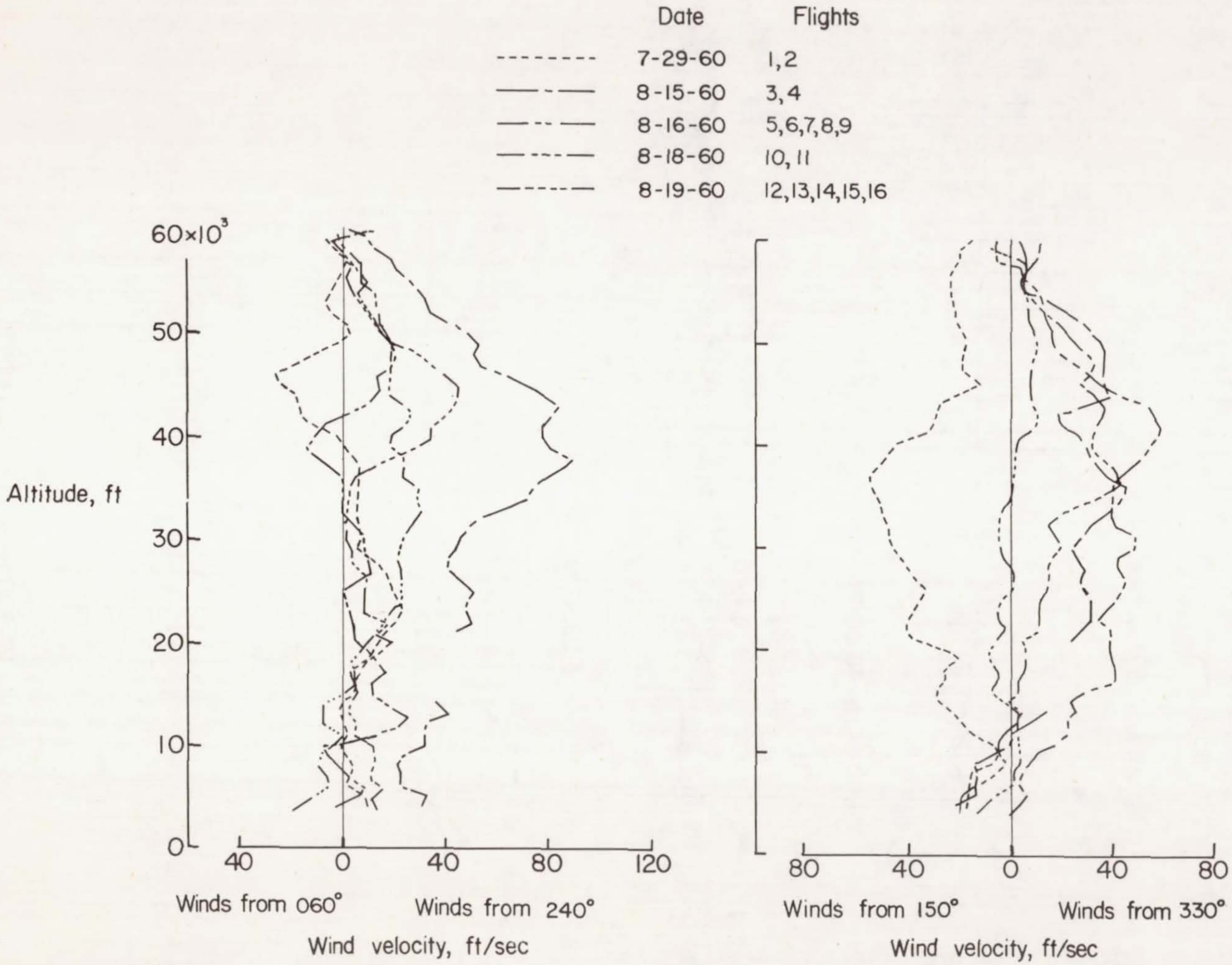


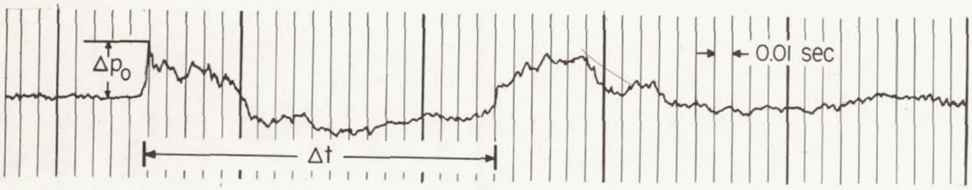
Figure 4.- Results from atmospheric soundings taken during test flights.



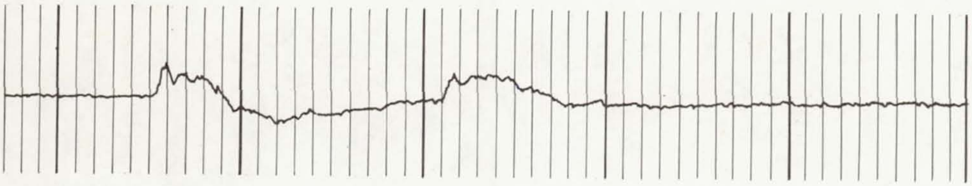
(a) Components along flight paths.

(b) Components perpendicular to flight paths.

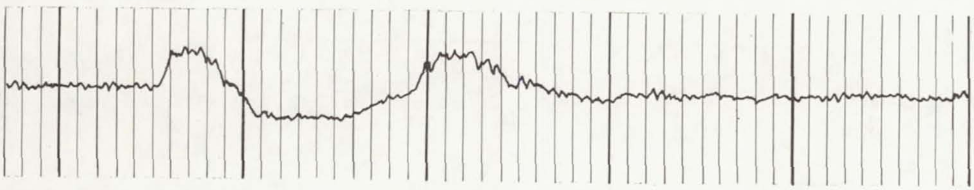
Figure 5.- Wind data obtained from atmospheric soundings taken during flight tests.



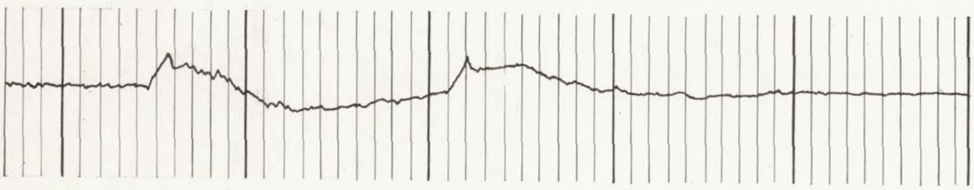
(a) Altitude 50,000 feet; M = 1.51; flight 2.



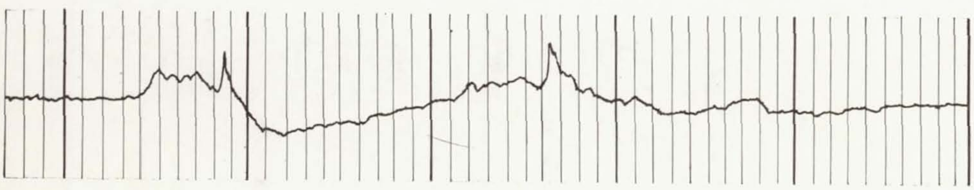
(b) Altitude 40,000 feet; M = 1.52; flight 14.



(c) Altitude 30,000 feet; M = 1.50; flight 9.



(d) Altitude 30,000 feet; M = 1.29; flight 11.



(e) Altitude 29,800 feet; M = 1.24; flight 15.

Figure 6.- Time histories of shock-wave ground noise pressures from flights at three altitudes as obtained with a microphone.

L-1457

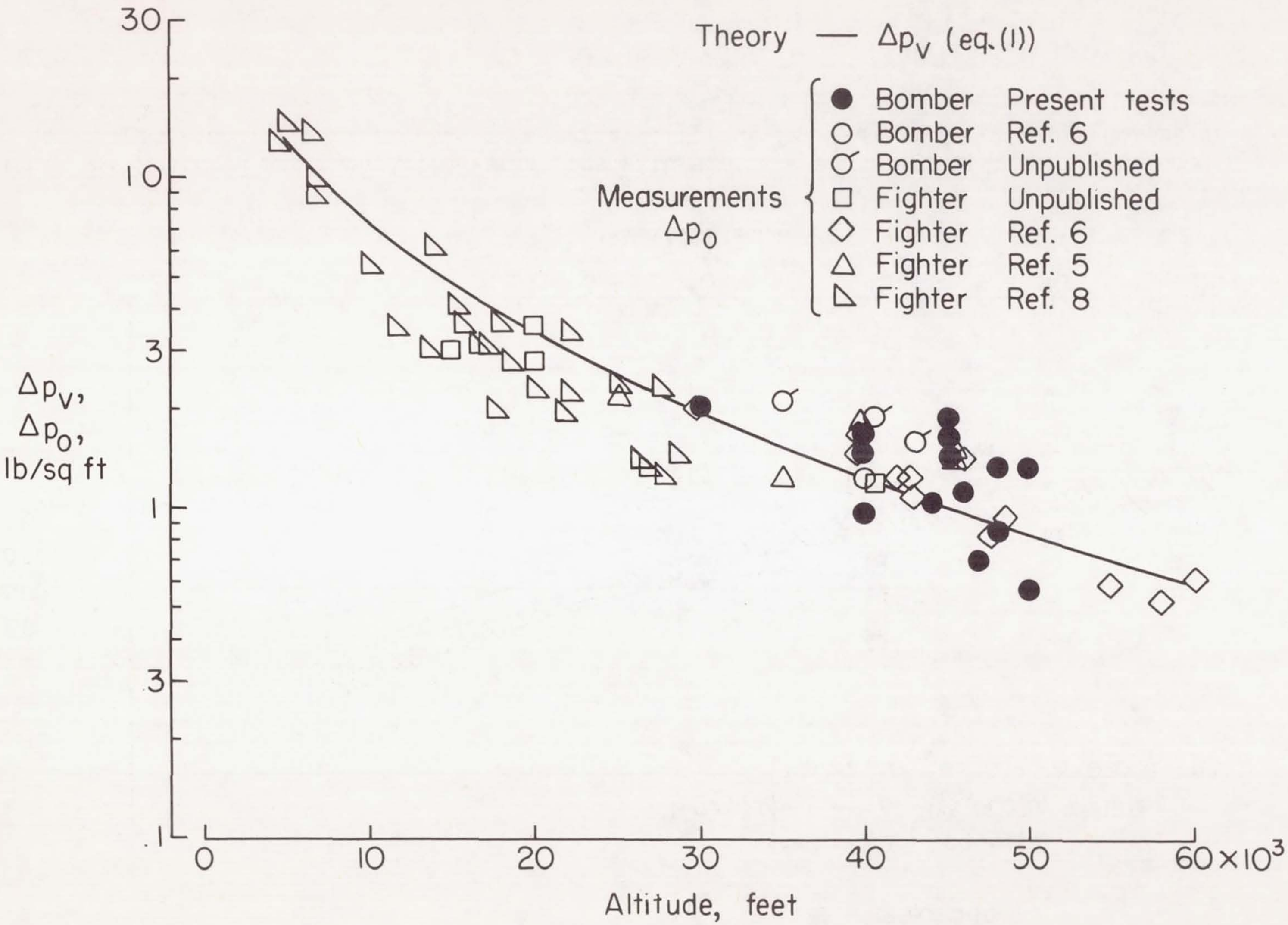


Figure 7.- Summary of ground noise pressures for fighter- and bomber-type aircraft. Open test-point symbols have been normalized to $l = 100$ feet, $M = 1.6$, and $\frac{l}{d} = 9$ by means of equation (1).

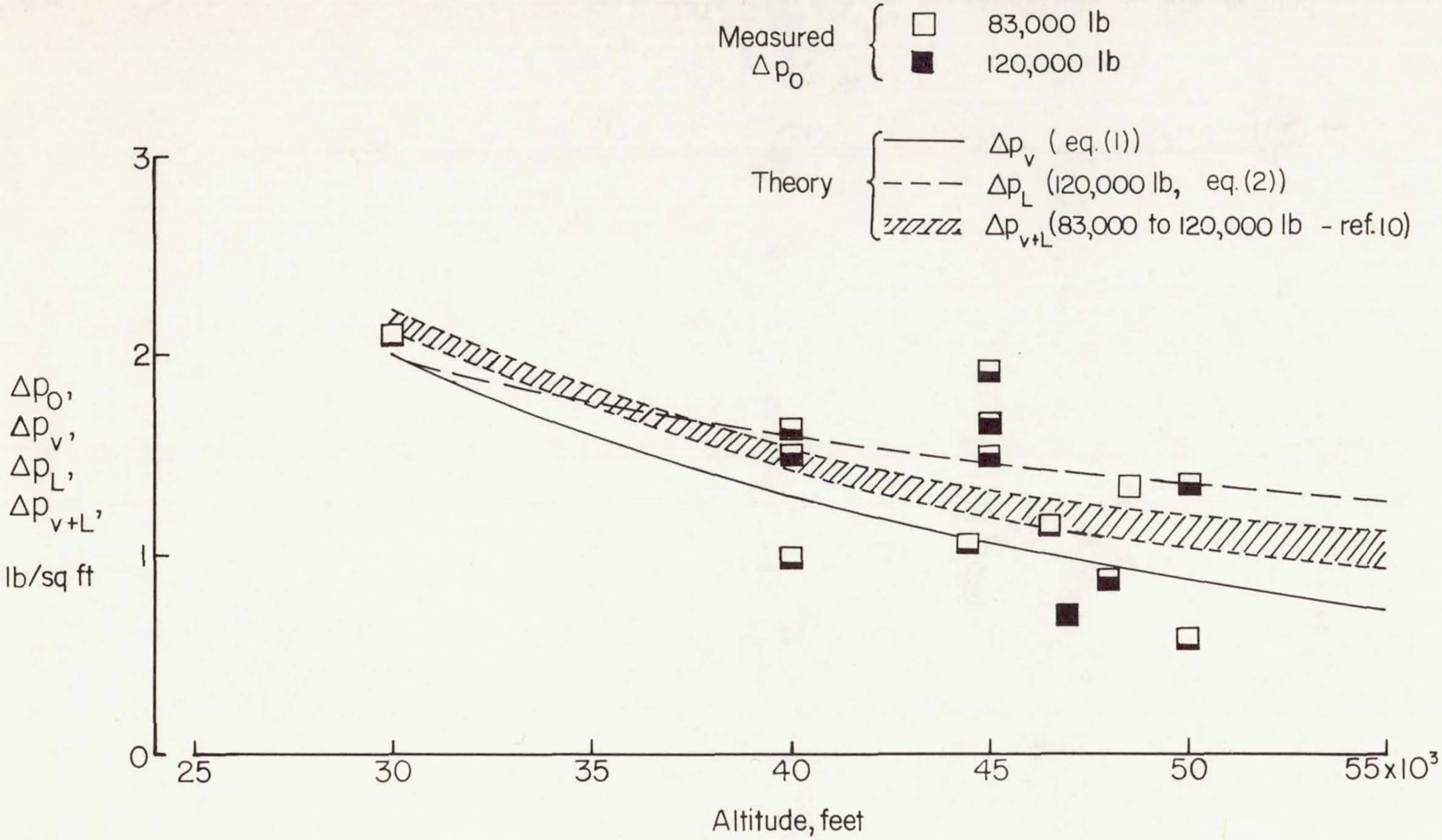


Figure 8.- Measured and calculated variations with altitude of the ground noise pressures near the flight track. Level flights on several different days were made at Mach numbers from 1.45 to 1.52.

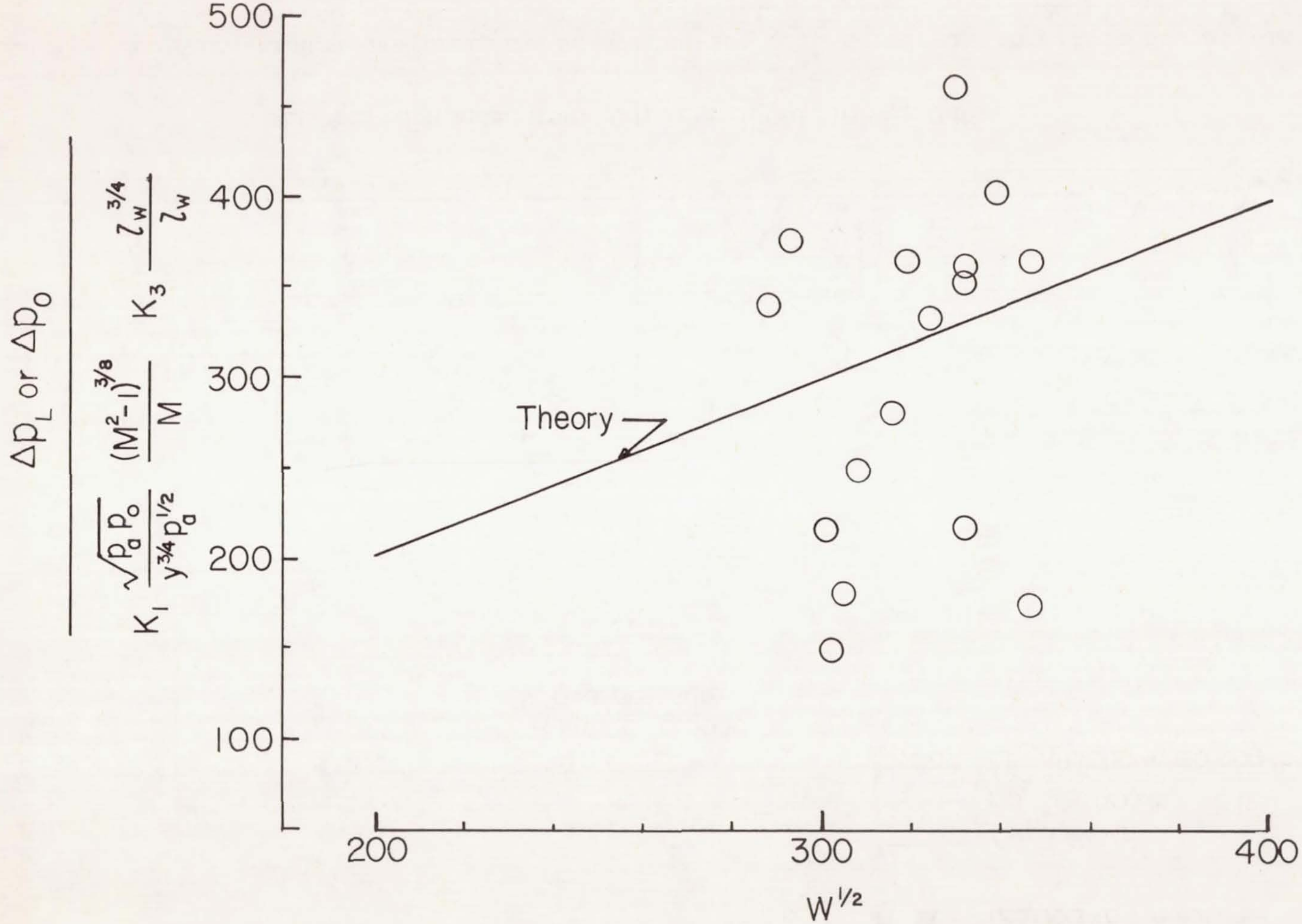


Figure 9.- Comparison of the measured and calculated effect of gross weight on the ground overpressure.

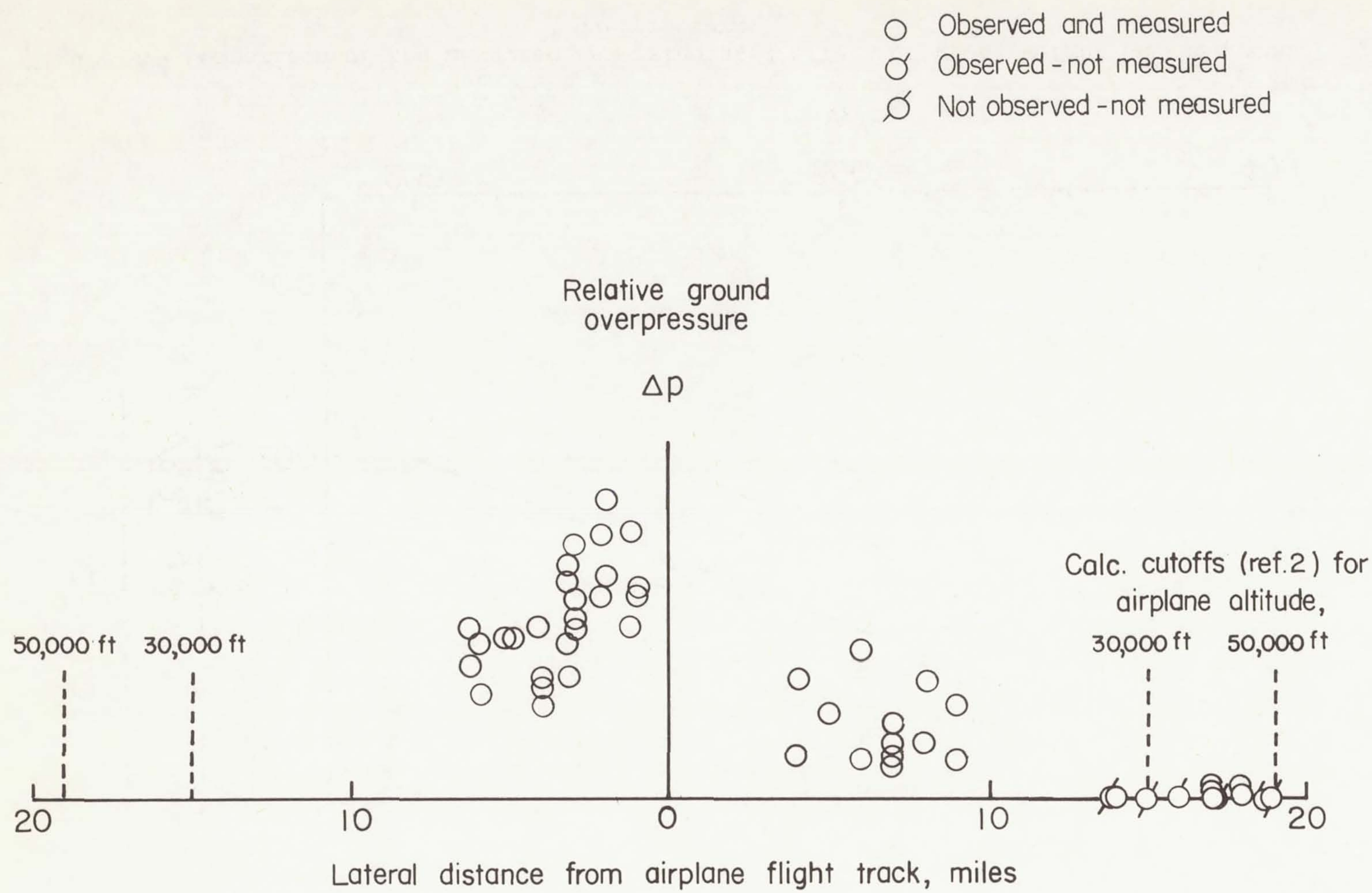


Figure 10.- Relative ground overpressure as a function of lateral distance from the airplane flight track as obtained by microbarograph equipment. Flights were accomplished at altitudes in the range from 30,000 to 50,000 feet, at Mach numbers from 1.45 to 1.52.

NASA - Langley Field, Va. L-1457